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- Comments:

Jon see attached

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Reference: Application of Medium Voltage Drive to Synchronous Motors

Jon,

Attached is an article by Richard Osman of Robicon. In this article he compares LCI technology to Series – Cell Multi-Level Inverters. Although Dick is an employee of Robicon, his technology and conclusions are generally accepted concepts and theories that have been proven in the field and accepted in Academia.

I hope you enjoy this information and that it helps in your selection of equipment process.

Best regards,

Mike

Mike Jackson
Riter Engineering Company

MJ:id

attachment

The Application of Modern Medium Voltage Drives To Synchronous Motors

By Richard H. Osman

In this paper we will compare and contrast the performance of the load-commutated inverter using a synchronous motor with that of a modern voltage-fed series-cell PWM inverter driving a synchronous motor. The technical considerations of retrofitting LCI's with multilevel series-cell voltage source VFD's will be discussed.

Synchronous motors have been used for over a century in high power industrial applications. They have achieved a reputation among electric machines for unsurpassed efficiency and excellent reliability. Their ability to help correct the user's power factor by supplying reactive power to the mains has also been an important benefit. However, the lower initial cost of induction motors has resulted in them being chosen for the vast majority of installations. Today, synchronous motors are almost exclusively limited to medium voltage machines of greater than 500kW rating.
After the introduction of the thyristor in 1957, serious variable frequency drives began to appear. But these SCR based VFD's required bulky, lossy and expensive commutating circuits to turn off the thyristors. Once gated, the SCR remains in the on state until the anode current goes to zero. For high power applications, the slow speed of the high voltage/high current thyristors meant even more cost in the commutating circuits. It was realized early that the SCR could be commutated easily—possibly without any additional circuits-- if the power factor of the load was leading. In that case, the current naturally reaches zero before the voltage, thus turning off the thyristor and allowing it to recover before the reapplication of forward voltage. In a few cases, such as induction heating, the load is a resonant tank circuit which lends itself to this. However, the magnetizing current requirements of the induction motor result in its always appearing as a lagging power factor load. Many techniques were developed before the advent of self-commutated switching devices in order to successfully use the SCR in an induction motor drive. (Meanwhile, the development of turn-off devices pushed on to the GTO, the power transistor, and recently the IGBT) However, in the case of the synchronous motor, one has the option of operating over a wide range of power factor, either leading or lagging. The flexibility of having the field input to maintain flux relieves the stator coils of that duty. If some way could be found to start the machine, the synchronous motor could be operated in a way to provide natural commutation of the thyristors without auxiliary components. In fact, a *very* early (1933) motor drive was constructed on this principle using ignitrons. (ref 1 Owen).

Load Commutated Inverter

Figure 1 shows the circuit of the load commutated inverter (LCI). Like most VFD's it has three stages. On the line side there is a thyristor converter, which changes the fixed voltage and frequency of the utility into variable DC voltage. This variable voltage is applied to the DC link choke, which blocks the voltage ripple and makes the DC link current smooth. The input converter is configured as a current regulator. On the machine side we have the same thyristor converter changing the DC link current into an AC current to feed the machine.

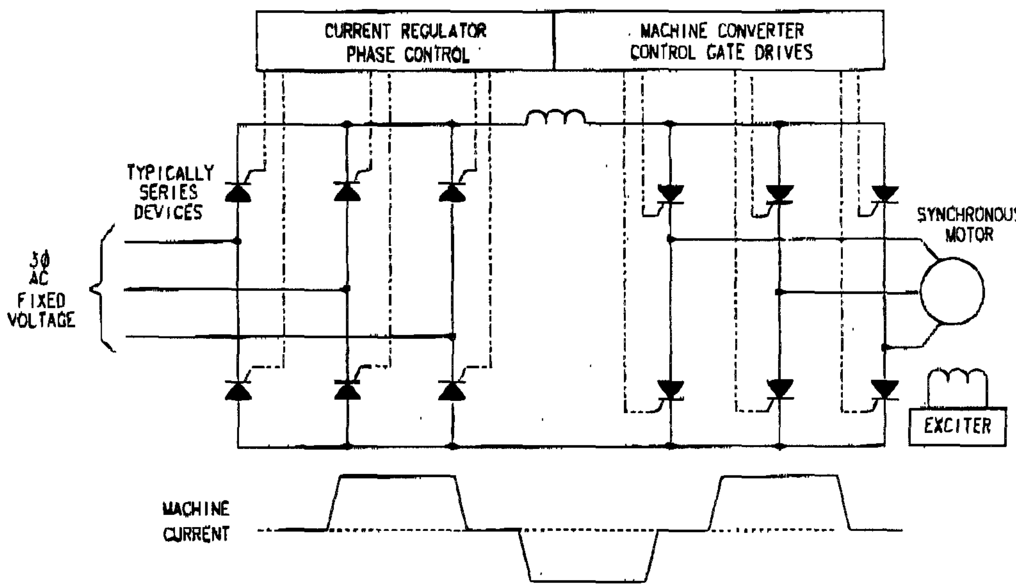


Fig 1 Load Commutated Inverter

The line-side and machine side converter operate in exactly the same fashion, except that the frequency and voltage are different. On the line side, the energy

to commutate the SCR's comes from the line. When the next SCR is gated, the line voltage drives the current down (to zero) in the offgoing device and up in the oncoming SCR. The rate of current change is dependent on the line voltage and source inductance. The same thing happens in the machine-side converter, except it is the back emf of the synchronous motor which drives the commutation, and the machine subtransient inductance controls the rate of change of current.

Neglecting commutation effects, the DC link voltage on the line side of the choke is:

$$V_{dc} = 3 / \pi \; V_{ullpk} \cos \alpha$$

Where Vullpk is the peak value of the input line-to-line voltage, and α is the phase back angle of the line side SCR converter.

An analogous relationship exists for the machine-side converter, since the waveforms are identical except for frequency:

$$V_{dc} = -3 / \pi \ V_{mllpk} \cos \varphi$$

Where Vmllpk is the peak value of the machine line-to-line voltage, and φ is the power factor angle of the synchronous motor. The negative sign comes from the fact that the machine side converter is inverted with respect to the line side converter.
These voltages are different only by the DC drop of the choke which is small, so practically we can say that:

$$V_{ullpk} \cos \alpha = -V_{mllpk} \cos \varphi \qquad 90° < \varphi < 180°$$

Since the motor voltage is usually equal to the input voltage at rated speed, the ratio of voltages can be replaced with the per unit speed:

$$\cos \alpha = (\text{PU speed}) (-\cos \varphi) \qquad 90° < \varphi < 180°$$

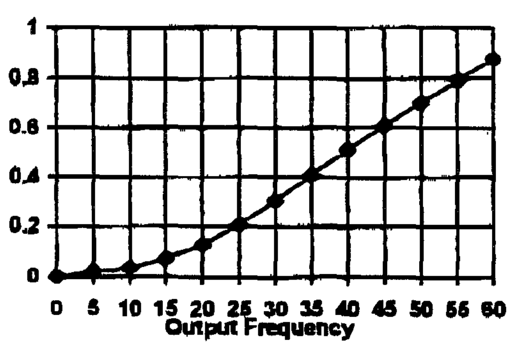


Fig. 2 shows the P.F. of an LCI used with a centrifugal load.

Since α is the converter phaseback angle, it also represents the delay angle of the input current with respect to the voltage. ***So we see that the uncorrected input P.F. of the LCI can never be higher than that of the motor times the PU speed.***
It is a well-known characteristic of current-fed topologies that the reactive power requirements of the load are passed back to the source.

It is clear that one would like to operate the machine-side converter at an angle of 180, but this is not possible. The motor terminal voltage which drives commutation vanishes at 180, so it is necessary to begin commutation well in advance of 180 in order to have time to successfully transfer the current to the incoming phase, and then have some reverse bias time on the offgoing SCR to permit it to recover. Typically, this is 150°, leading to a P.F. of .866. However, one would like to be able to get as close to 180 as practically possible, which means as short a commutation interval as possible. It is important to minimize the commutation interval in order to keep the machine P.F. as high as possible.

(On the line side, there's no problem as the source inductance is very low.) But the machine subtransient inductance controls the rate of change of current, and hence the commutation time. It is usually necessary to design the machine to keep the subtransient reactance below 17%, frequently necessitating a special design.

The relationship among these variables is:

$$\int_{180}^{\alpha} V_{llpk} \sin \omega t \, dt \; > \; 2 L_s I_{dc}$$

$V_{llpk} \sin \omega t$ is the voltage driving commutation. The volt-seconds available from the time commutation commences until the end of the cycle must be greater than $2 L_s I_{dc}$ if commutation is to be successful. Ls is the per-phase source inductance, which is the subtransient inductance in the case of a synchronous motor. A more detailed analysis of LCI's is given by (ref 2, Rosa).
Early LCI's used rotor position detectors to keep track of the position of the machine cemf, and thus when to begin commutation. This technique is still used, but using the motor terminal voltage to operate a phase control circuit has become more popular, as it eliminates the need for the rotor sensor. This sensor needs to be carefully aligned as the flux has a specific orientation with respect to the rotor, in contrast with the induction machine.

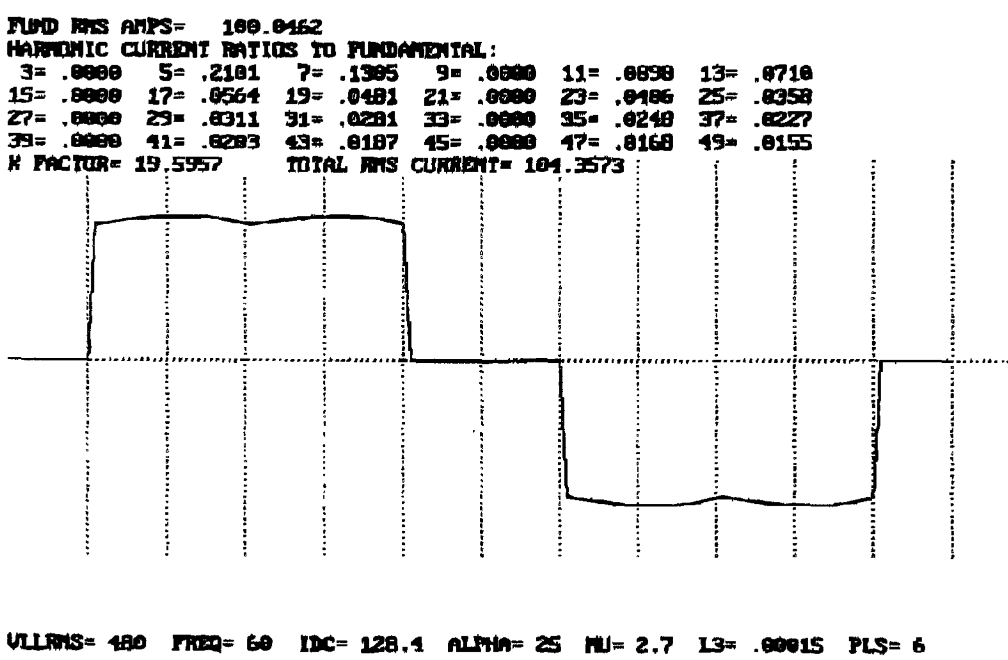


Fig. 3 Typical Input Current to a 6-Pulse Current Fed Circuit

On the input to the line side converter, we see a quasi-square wave of current in the line. (Fig 3) The DC link current is connected to the input AC lines in sequence. The commutation time is short, typically 3-10° of the line cycle, so there are significant high order harmonics present. Fig. 3 shows the harmonic spectrum of a 6-pulse thyristor converter with 5% source inductance. There are multipulse mitigation techniques for the harmonics. For example, one can stack two converters in series and use a phase shifted supply to eliminate the 5^{th} and 7^{th} and all harmonics which are not 12*N +- 1.

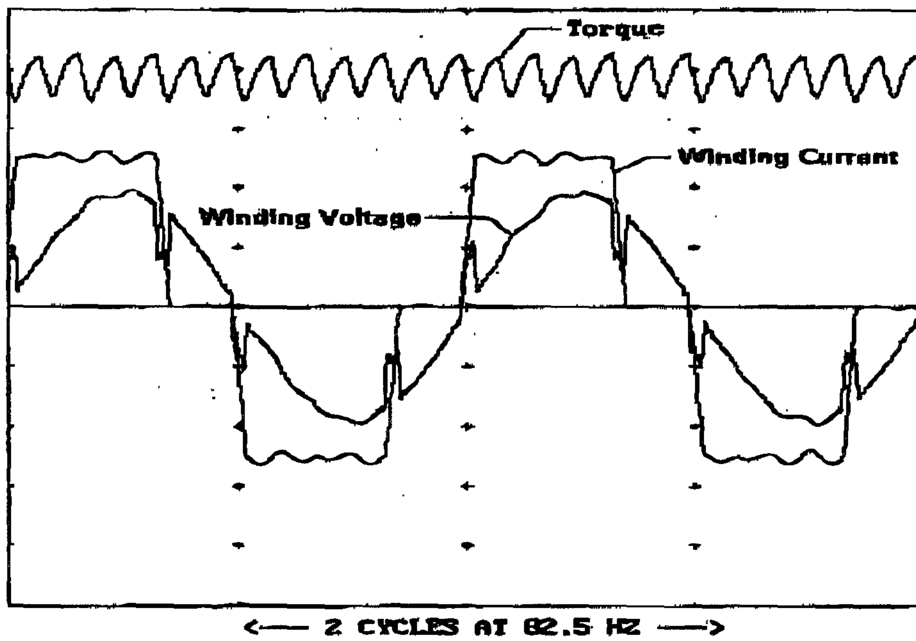


Fig 4 LCI Output Current Waveform

Nevertheless, even the 12 pulse input circuits do not meet the most stringent requirements of IEEE-519, i.e., less than 5% current harmonic distortion. So in order to have good input power quality, it would be necessary to use additional filters to restore the power factor and absorb the harmonic currents.

Since the machine side converter operates in exactly the same way as the line side converter, the motor currents look like the line currents, except that the rate of change of current is smaller. Fig. 4 shows a typical output current wave for an LCI. In this case, there are 2 output converters feeding a single machine, and we see one 6-p winding current, but the torque ripple is 12-p. The commutation time is about 6°. This waveform has the usual 1/h harmonic spectrum of a square wave, with the harmonics divisible by 3 absent. For a 6-pulse converter, the current distortion is about 30%. This harmonic current has several adverse effects on the machine:

1. It increases the RMS current in the machine by about 5%, but does not add any useful output torque. This raises the copper losses in the stator windings and the dampers.
2. The time harmonics in the motor current become space harmonics in the stator MMF which causes torque pulsations. The stator MMF advances step wise 60° at each commutation, but the flux moves more or less uniformly. Thus, a step of torque is produced each time the stator current changes abruptly. These torque pulsations occur at 6 times the stator output frequency. It is possible to mix the output of two converters in a transformer or in a six winding motor, in which case the torque pulsations are reduced in amplitude and occur at 12 times the stator output frequency. Of course, the danger is that these torque pulsations will excite a mechanical torsional resonance.
3. Since the flux in the machine is trapped by the damper windings, the harmonics in the stator current give rise to offsetting harmonic currents in the damper bars and end rings. This is not a problem if you have an induction machine where the rotor bars are sized to handle rated current continuously. But in a synchronous machine, the damper bars may have to be upgraded to carry the large harmonic currents which must continuously flow.

A more subtle difficulty with the LCI and all current-fed drives is the large common mode voltage applied to the machine if there is no transformer on the input. (ref 3 DeWinter) High common-mode voltage requires the machine insulation to withstand abnormally high potential from the stator windings to ground. If no other means are provided to control the common-mode voltage, a special high-voltage insulation system is necessary. Of course, the input transformer is generally required to step the utility voltage down to the level of the power conversion circuits, and to provide the input phase shifting for 12-pulse operation.

Another drawback of the LCI is the difficulty in starting it. Under normal operation, the counter emf of the machine commutates the inverter thyristors. But below 10% speed (approximately), there is not enough induced voltage to successfully commutate (see eqn. 4). In order to start the LCI, it is necessary to interrupt the DC link current by phasing back the line side converter, in order to permit the inverter thyristors to commutate. A current interruption is needed between at each change of state of the inverter. In this mode of operation, the torque pulsations can become very large (1 PU) if rated link current is needed to break the load free.

Despite these drawbacks, the LCI has been a commercial and technical success in the VFD arena. However, there are more recently developed MV drives which use modern semiconductor switching devices that can overcome these limitations. One such VFD is the Perfect Harmony, which is a series-cell multi-level drive based on IGBT technology. Fig. 5 shows the power circuit of the Perfect Harmony.

Series-Cell Multi-Level Inverter

The Perfect Harmony is a voltage-fed drive. Therefore, the reactive power requirements of the load are supplied from the DC link capacitors in the cells and not the line. So the power factor is above .95 under all load conditions. The Perfect Harmony uses input multi-pulsing to totally reduce input harmonics. For a balanced supply, the input current THD is less than 3% for 3-cell units and less than 1% for 5 cell units. There is no need for any power factor correction or harmonic filters on the input. Fig. 6a and 6b shows the input current and voltage and the output voltage and current to a 2250Hp 4kV Perfect Harmony.

Due to the large number of voltage steps on the output and clever PWM modulation, the output voltage is incredibly low in harmonics. The current is nearly indistinguishable from a pure sine wave, and this is the case at all output frequencies and loads. The purity of the output current eliminates all torque pulsations.

Since the IGBT's in the drive can be turned off and on at will, there is no need to operate at any specific motor power factor. Therefore, the machine and VFD can be utilized to the maximum extent possible by unity power factor operation. This property also frees the motor design from a subtransient reactance constraint. Therefore, for a new installation, there are savings to be had in the synchronous motor as it can be smaller (higher reactance) than it would have had to be for an LCI. The VFD does not care what the motor power factor is, and machine reactive power is not drawn from the utility, unlike the LCI and other CSI based drives.

Since only real power is drawn on the input, in the no-load case extremely low input current is needed; only transformer magnetizing current and loss makeup current. Furthermore, starting on the Perfect Harmony is the same as running; a very low frequency, low harmonic sine wave of voltage is applied to the machine, and starting is free from torque pulsations. The absence of motor harmonic currents means that there is no machine de-rating necessary, nor do the damper bars carry any current in steady-state operation. To summarize, a completely standard synchronous motor designed for utility operation can be used with the Perfect Harmony drive. Of course, retrofits are feasible too. The only special requirement applies to the brushless excitation system, as we will explain

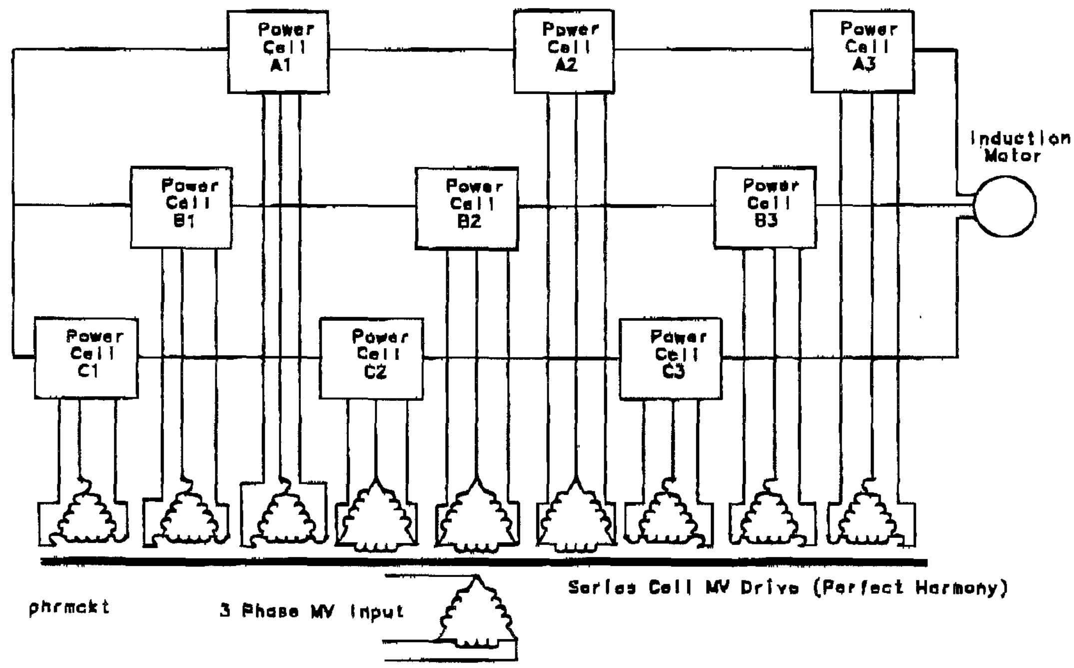


Fig 5. Perfect Harmony MV drive

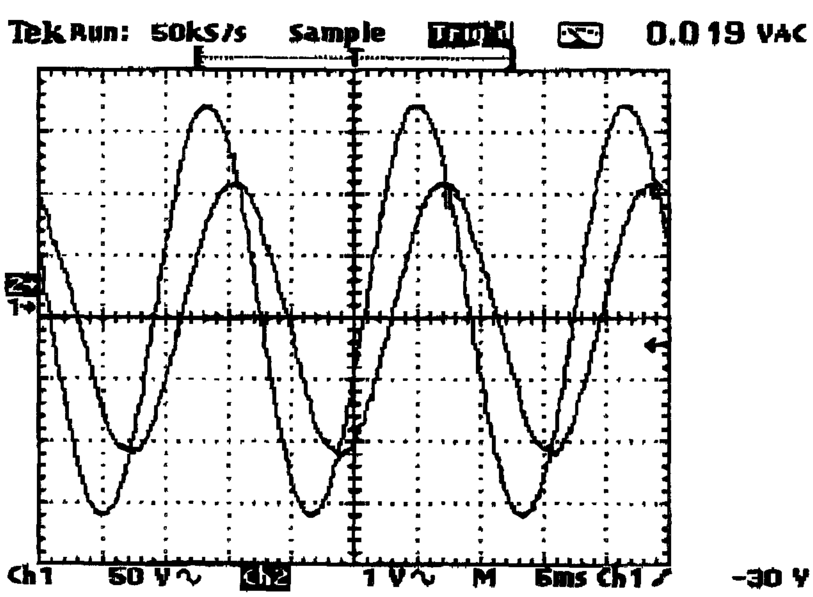


Fig 6a Drive input - 1/24/00 @ 1:00 pm
Ch.1 - Line A to B Voltage 1.75kV/div
Ch.2 - Line A Current 160A/div
Operating Point 5 - 100% Load
Drive input 241A / 4310v / 1750kW / 60Hz

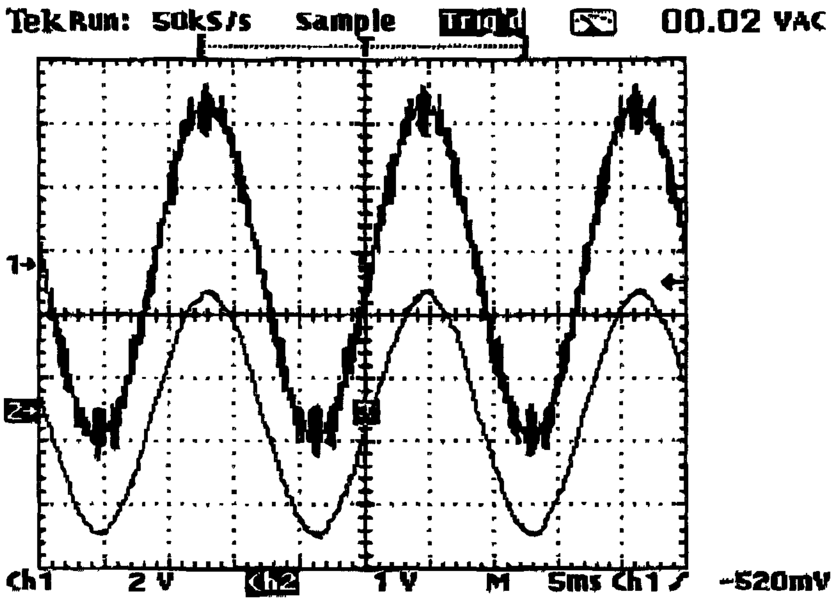


Fig 6b Drive Output - 1/24/00 @ 1:00 pm
Ch.1 - C Phase Motor Voltage -Vcn
Ch.2 - C Phase Motor Current IcFdbk
Drive output 251A / 4004v / 1712kW / 60Hz

A complete brushless synchronous motor drive schematic with a Perfect Harmony VFD is shown in fig 7. The complete system consists of 3-3750Hp drives and 2-2250Hp drives. One drive is shown including the constant speed bypass equipment. A somewhat special arrangement is needed for the field excitation.

There are two field exciters consisting of a three phase 6-SCR AC switch which supplies power to the stator of the exciter. One exciter is for line operation, and one for VFD operation. This arrangement is for redundancy; one exciter can be used for both modes of operation.

Ordinarily, for constant frequency line operation, the brushless exciter machine would have a three-phase winding on the rotor and a single winding DC stator. After the synchronous machine has been brought up to speed by induction torque caused by currents in the damper bars, DC excitation is applied to the exciter stator, and the voltages induced in the rotor windings due to the rotation of the rotor with respect to the fixed stator flux, are rectified and applied to the main field. The application of field voltage is governed by a synchronizing circuit on the rotating rectifier assembly. It controls the field by firing the pass SCR at the appropriate time when the motor is almost at synchronous speed. This is determined by the frequency of the inducted field currents when the machine is below synchronous speed.

In a VFD application, there are no speed voltages at standstill, and the power to the field must be passed by transformer action through the exciter machine, which is essentially a wound-rotor induction motor. During starting of the synchronous motor on the VFD, the field excitation is applied first to establish flux. (Since the synchronous reactance is much lower than the magnetizing reactance of an induction motor, it would take too much stator current to create the flux without field current.) When the exciter rotor voltages are rectified by the rotating rectifier, the synchronizing circuit is energized; but it doesn't see any induced field current, because the stator MMF hasn't been applied. So, after a short pause, it fires the pass SCR to allow the rectifier DC output to reach the field.

Then the stator voltage is applied by the VFD, in the form of a very low frequency voltage. This causes stator current to flow, but not the locked rotor amps seen during line starting. Only rated current or less is applied. The stator MMF generated by the current reacts with the field flux, and torque is produced. The rotor turns to align the flux and MMF, and synchronization occurs at this time. Then as the frequency increases, the stator MMF begins to rotate slowly. This causes the torque angle to increase, and synchronous torque is produced to make the rotor follow the stator. The machine does not start as an induction machine; synchronous torque is developed at standstill and during acceleration, unlike line starting. Therefore, the damper bars do not experience any current or heating. This means that unlimited starts can be made, and there is no thermal cycling of the bars to cause deterioration of the rotor structure.

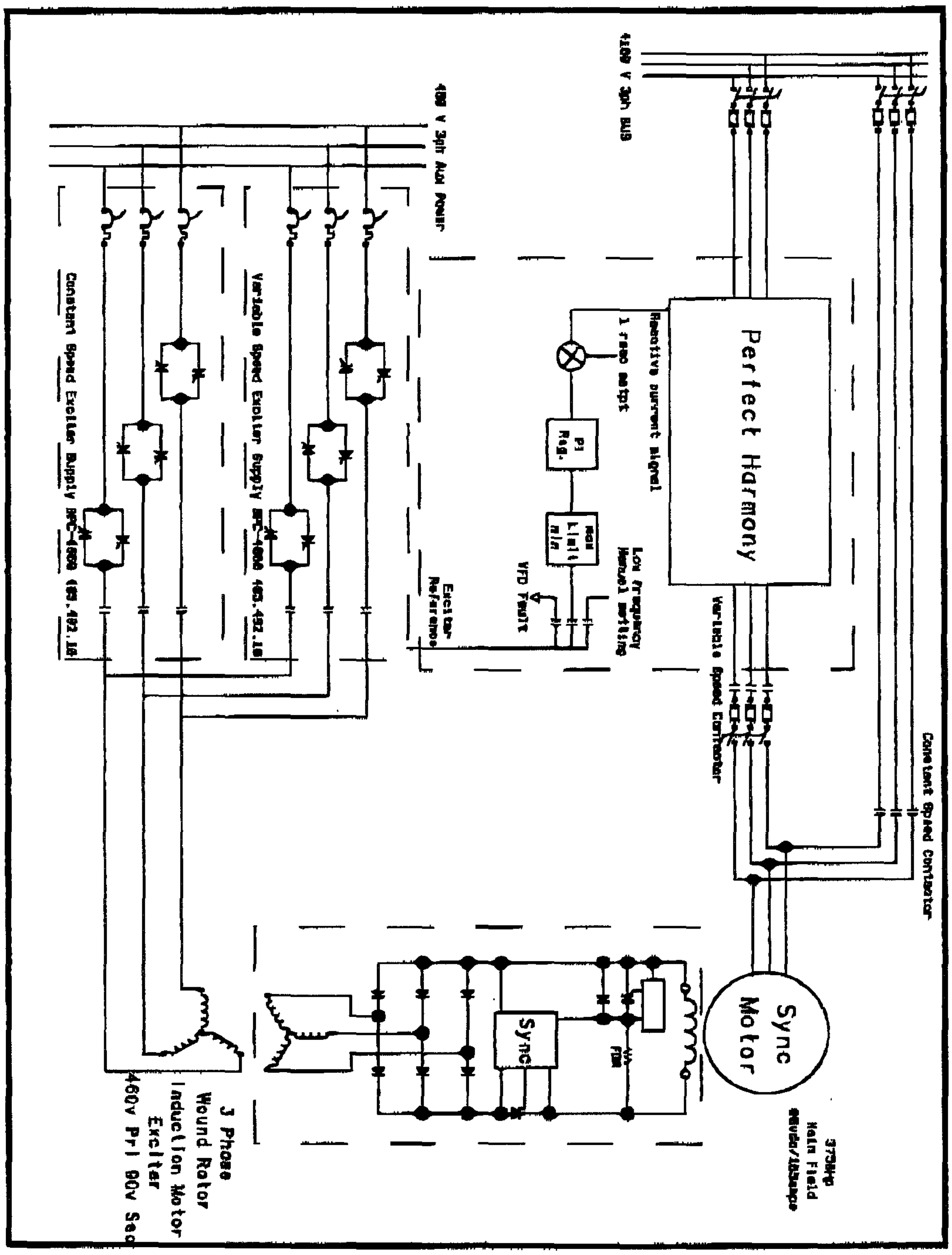
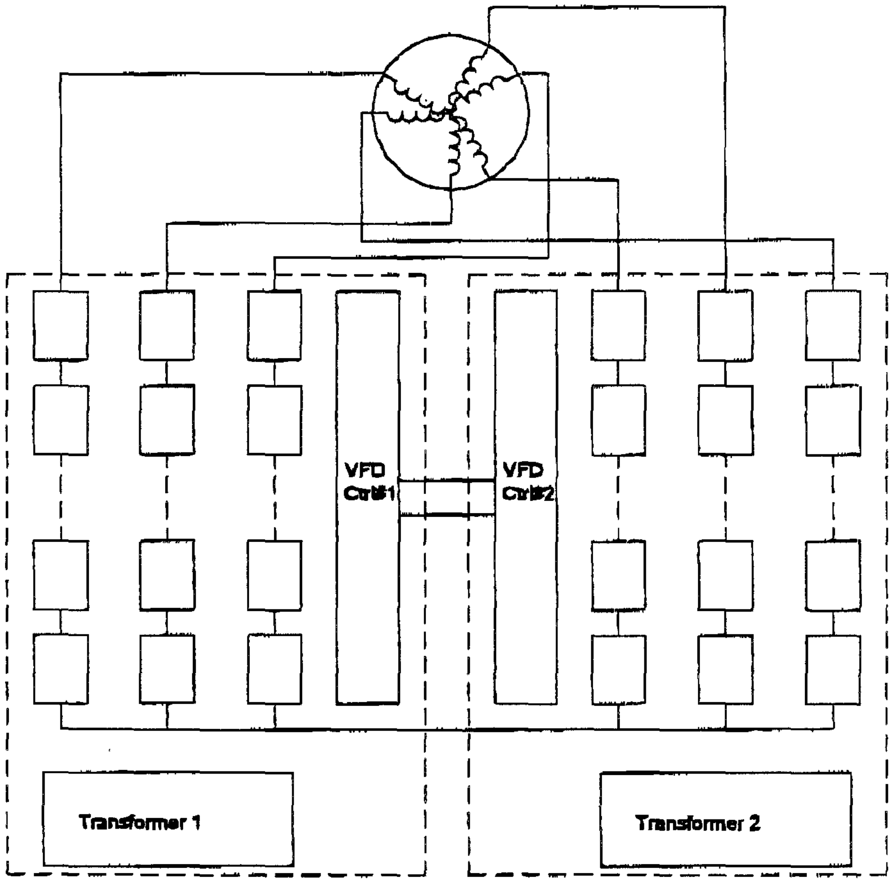


Fig. 7 Synchronous Motor drive system with Perfect Harmony VFD

Due to the longevity of the LCI, there are many such drives in service today, and they are still being constructed for certain applications like turbine generator starters. The synchronous motors have a much longer service lifetime than the power electronics because of the progress of drives development. It can be difficult to obtain spares and service on power electronics more than 15 years old, but large AC motors of that age are still in their prime, and can be maintained for decades. Therefore the question arises if it is possible to retrofit LCI's with more modern power electronics to obtain better performance and maintainability. The answer is almost always yes. This is partly because the synchronous motors for LCI's are robustly designed to cope with the non-ideal waveforms of the LCI power electronics, and that derating is not necessary for multilevel series-cell VFD's. To be specific, the LCI current distortion requires the motor windings to carry about 5% more rms current than the fundamental. The fundamental current generates the torque, but the rms current determines the winding heating. If the motor has a single 3-phase winding of a "standard" voltage, like 2400, 3300, 4160, 4800, 6000, 6600 or 7200 volts, then applying a Harmony drive is very straightforward. Then a single VFD is sized for machine rated voltage and current. A complication is that a common design practice for LCI drive systems was to use non-standard machine voltages to match the power electronics, and also to use 6 phase windings in which there are two separate 3-phase windings phase displaced by 30 degrees electrical. These situations require more imaginative VFD solutions.
There is generally no need to change the exciter machine on the motor when retrofitting from an LCI to a Harmony drive. Also, the Harmony requires no tachometer or rotor position indicator on the motor.
The modularity of the Harmony solution lends itself to the need to attain "odd" voltages. In the cases in which there are two 3-phase windings there are at least two possibilities:

1. The most straightforward approach is to use two Harmony drives each rated for half the motor power, like the LCI. The Harmony drives can be interconnected to operate together into a single motor.

2. Another possibility is that the two sets of windings can be interconnected into one 3-phase winding. This is particularly interesting if the original winding voltage was around 1200 or 2400 V line-to-line. This requires that all the coil ends be accessible in the terminal box, and the winding insulation system is capable of handling the resulting higher voltage. By connecting the two windings with a 30 degree shift in series, we obtain effectively a single winding with rated voltage of 1.93 times the original. For example if the original windings were 1100 volts, the reconnected winding is rated 2125 volts, which a 2300 volt Harmony drive can readily feed. This practice was described in IEEE P995 for testing 6-phase motors on 3-phase supplies.



Case 1. Two Harmony drives operating a 6-phase motor

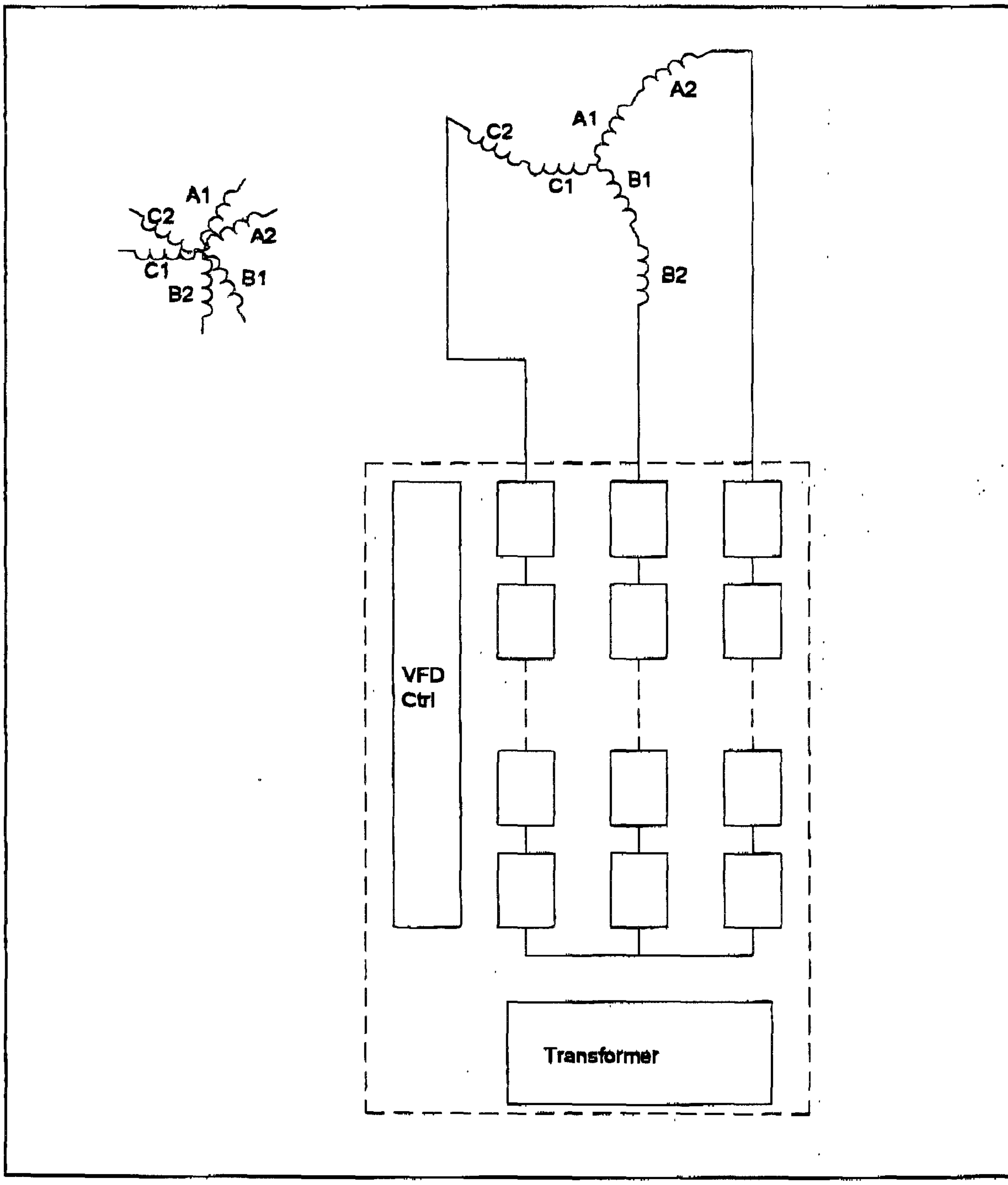
Disadvantages:

More expensive and physically larger than the single VFD solution.

Advantages:

Can operate with only one VFD in service.

Lower voltage stress to ground.



Case 2. One Harmony drive operating a 6-phase motor reconnected to 3 phases.

Advantages:

Less expensive than the two VFD solution.

Disadvantages:

No redundancy

Higher voltage stress to ground.

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